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CO_2 Geological Storage in the Province of Québec, Canada – Capacity Evaluation of the St. Lawrence Lowlands basin

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Abstract

The evaluation of the storage capacity of the St. Lawrence Lowlands basin was performed in the Province of Québec (Eastern Canada). The Covey Hill and Cairnside formations have global porosities of 5% and 3%, which is enough to be considered in the basin-scale storage capacity evaluation. The efficiency factors used in the capacity calculation are defined in the Carbon Sequestration Atlas of the United States and Canada and range from 0.51% to 5.4% in clastic sedimentary units. Two 3D geological models of the basin were used to represent the potential reservoir units at the basin-scale: uniform and faulted basin. This allowed calculating the volume of the potential reservoirs and comparing the capacity of a large-scale uniform basin with a faulted basin compartmentalized by the existing normal faults.

Keywords: basin; assessment; screening; CO_2; storage; CCS; Québec; Canada.

1. Introduction

The Government of Québec, in Eastern Canada, has the objective to reduce its greenhouse gas emissions of 20% compared to 1990 by 2020 [1] and decided to explore CO_2 geological storage as an option for reaching this reduction target. There are five sedimentary basins in southern Québec which can be considered for CO_2 storage potential: 1) the St. Lawrence Lowlands basin, 2) the Anticosti basin, 3) the Appalachian basin, 4) the Gaspé Belt basin and 5) the Magdalen basin (Figure 1). An assessment of the CO_2 storage potential in the Province of Québec showed that the Gaspé Belt and Appalachian basins should not be studied furthermore because of the lack of data and the complex geology [2]. The Anticosti

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and Magdalen basins could be studied in the future because they demonstrate good storage potential but their offshore and remote settings are to be considered. The basin-scale assessment for CO_2 storage potential in Québec sedimentary basins identified the St. Lawrence Lowlands basin as the most prospective basin [2] and which encompass many large CO_2 emitters (Figure 1). This paper presents the evaluation of the storage capacity of this basin using two types of 3D geological models: a uniform basin and a faulted basin compartmentalized by the existing normal faults.

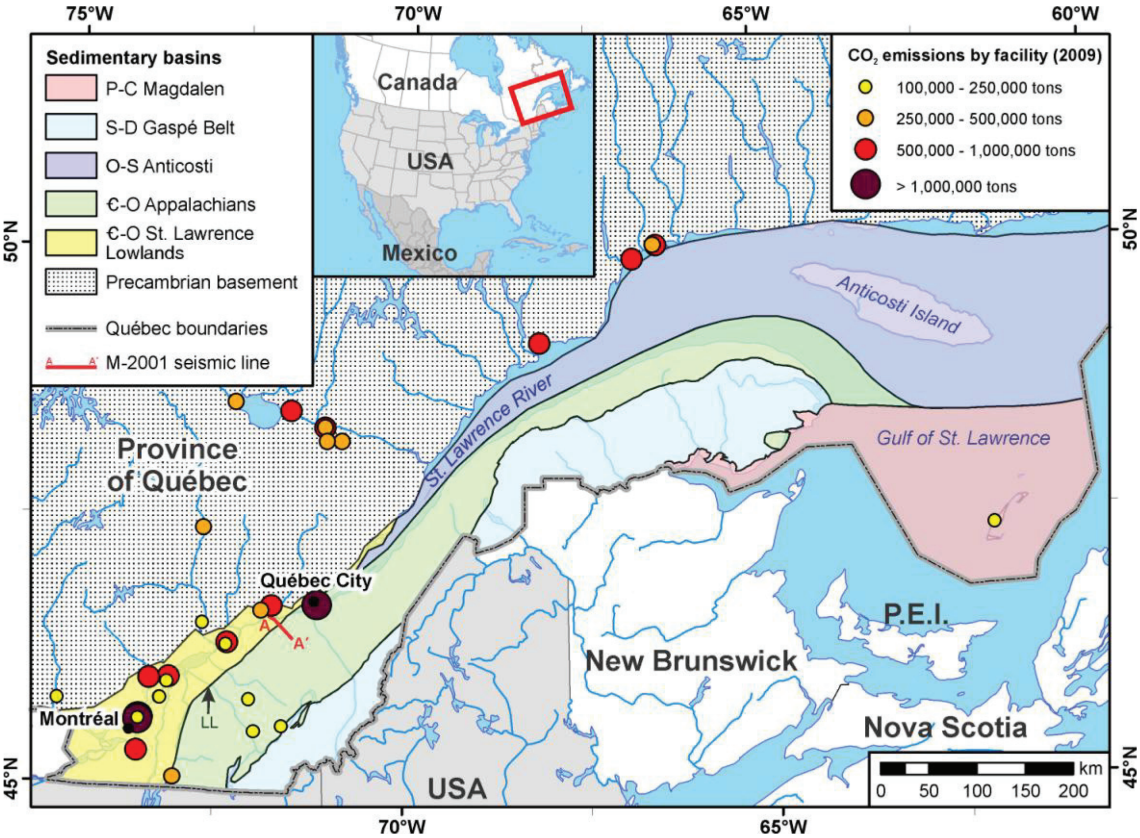

Fig. 1. Distribution of sedimentary basins and major sources of CO_2 in the Province of Québec. LL: Logan's Line; P.E.I.: Prince Edward Island. Data source for CO_2 emissions: Environment Canada [3].

2. Geological settings of the St. Lawrence Lowlands basin

The Cambro-Ordovician platform sequence of the St. Lawrence Lowlands unconformably overlies the Precambrian basement and has a thickness of up to 3000 meters [4]. NE-SW trending normal faults affect the lithostratigraphic units which deepen toward the south-east (Figure 2). The sedimentary sequence is composed of sandstones of the Potsdam Group, dolostones of the Beekmantown Group and limestones of the Chazy, Black River and Trenton groups (Figure 2). They are overlain by shales and siltstones of the Utica Shale and Lorraine Group, which are considered as the ultimate caprocks for CO_2 sequestration. Only platformal sedimentary rocks are evaluated for CO_2 storage as they contain deep saline aquifers in the Potsdam, Beekmantown and Trenton groups. The thrust slices, which may contain gas reservoirs, are not evaluated in this study (e.g. St-Flavien thrust slice, Figure 2).

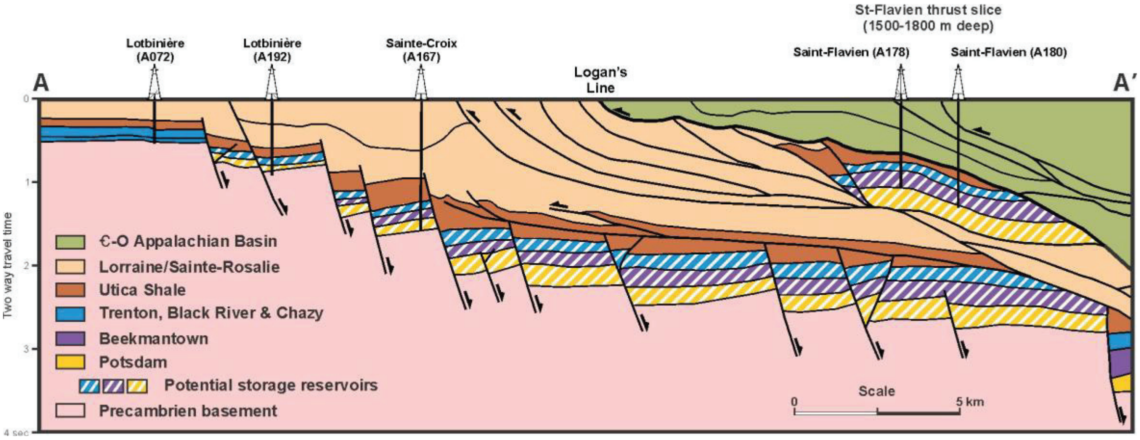

Fig. 2. Architecture of the St. Lawrence Lowlands basin based on the M-2001 seismic profile. See Fig. 1 for location. Modified from [5].

3. Construction of the 3D geological model

The 3D geological models of the basin were created in GOCAD® software as the basis for the CO_2 storage capacity analysis. The first step was to model the Precambrian horizon with the structural map in time (for the geometry) and the well data (for depth). Although the Precambrian basement depth in microsecond (two-way time) from seismic data [6] could not be used "as is" because there are no one time-to-depth conversion algorithm for the whole basin, it was used to constrain the geometry of the Precambrian basement surface with depth based on well data (Figure 3).

Reinterpreted formation tops in wells with logs [7] were used in this study as the basis for the interpretation of the formation top in depth. The surfaces of the selected formations/groups were modeled with the formation tops in well as hard data for depth. The horizons were interpolated between the wells with the interpolation method developed specially for geological interpretation in GOCAD®, which is called Discrete Smooth Interpolation (DSI). The surfaces where then manually edited to remove the inappropriate cross-overs and to assure the model integrity.

The 3D faulted model was divided by normal faults affecting the Precambrian basement based on seismic interpretations (Figures 3 and 4). Since these normal faults are also recognised on the structural map of the top of Trenton Group [8], it is assumed that these normal faults entirely cut all the units at the base of the sedimentary sequence.

Finally, a 3D voxel[†] model was created in order to represent the volume of each of the analysed formation/group (Figure 5). The voxel model has a length of 240 km (NE-SW axis), a width of 130 km (NW-SE axis) and a thickness of 7500 m (vertical axis). The individual cells are longer in the NE-SW direction because of the structure of the basin shows less variation in this direction (1000m × 750m × 10m).

[†] Voxel: volume element, three dimensional cell. The 3D equivalent of the pixel.

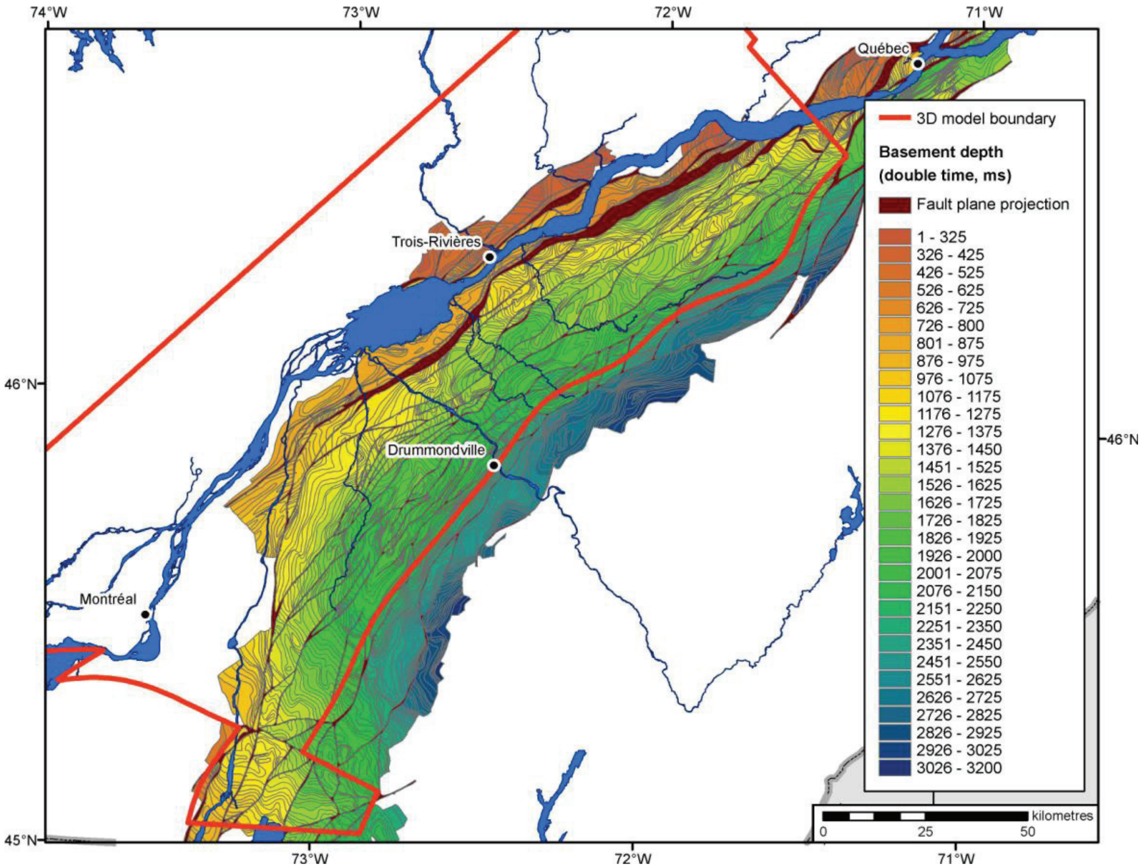

Fig. 3. Extent of the 3D model (black line) and wells (yellow dots) used in this study showed on the structural map of the Precambrian basement top based on seismic data. Data source: MRNF [6].

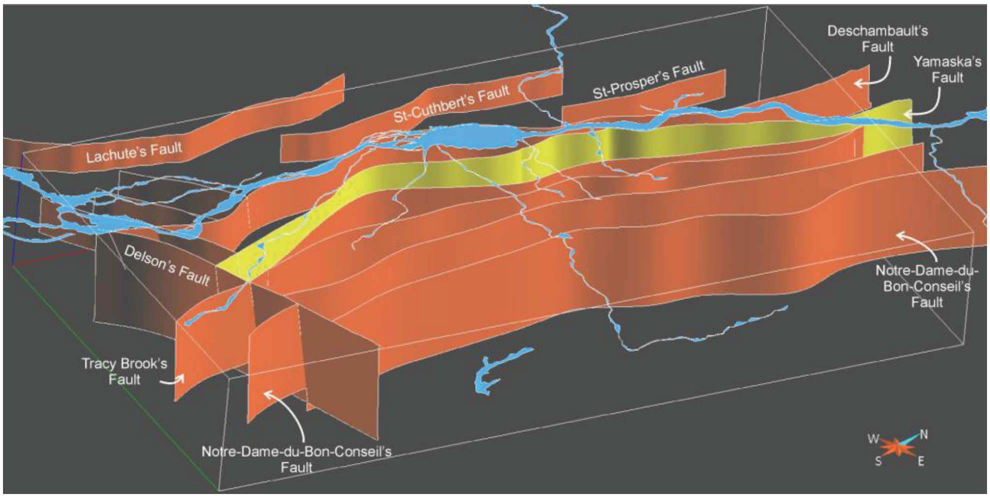

Fig. 4. Geometry of the normal faults used in the 3D faulted basin model.

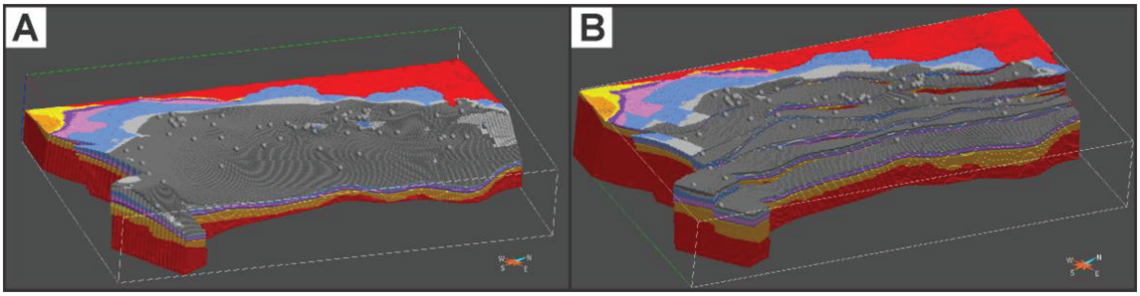

Fig. 5. Both 3D voxel models of the St. Lawrence Lowlands in Québec: a) uniform; and b) faulted. Color dots show where wells cross formations. Vertical exaggeration: 5X.

4. Storage capacity parameters

The storage capacity is calculated following the equation (1):

$$M_{CO2} = E_{saline} \times A \times h \times \varphi \times \rho CO_2 \quad (1)$$

M_{CO2} :	CO_2 mass (kg)
E_{saline} :	CO_2 storage efficiency factor for saline aquifers
A :	area of the reservoirs (m^2)
h :	gross thickness of the reservoirs (m)
φ :	porosity of the reservoirs (%)
ρCO_2 :	CO_2 density in depth (kg/m^3)

4.1. Porosity (φ)

Porosity is one of the restrictive parameters for CO_2 sequestration [9]. In the St. Lawrence Lowlands basin, 21 wells had core analyses which allowed calculating an average porosity of each of the formation in the basin. Only the Cairnside and Covey Hill formations have average porosities of more than 3%. The other formations were then excluded from the final analysis because they do not show good porosities at the basin-scale for CO_2 sequestration. To account for the bias from core selection (cores are preferentially analysed in porous zones), the average porosity was rounded to a lesser value. The arithmetic average porosity for the Cairnside Formation is 3.75% and 6.10% for the Covey Hill Formation, whereas the rounded values we use are 3% and 5%, respectively for Cairnside and Covey Hill formations.

4.2. Storage efficiency factors (E)

The factors used are defined in Table 7 of the Appendix B of the Carbon Sequestration Atlas of the United States and Canada [10]. These *E* factors in saline formations for clastic rocks, such as sandstones of the Cairnside and Covey Hill formations, are 0.51%, 2.0% and 5.4% for P_{10}, P_{50} and P_{90} percent confidence intervals, respectively.

4.3. Area (A) and gross thickness (h)

The gross area and gross thickness parameters are normally used to determine the volume of the analysed formations. As a 3D model is used, the gross volume is directly calculated in GOCAD® software. No effective aquifer thickness (and therefore, volume) is calculated as there are not enough data to constrain the interpretation. Moreover, when using the « efficiency factors for geologic and displacement terms » defined above, the gross thickness of the formation should be used as the factors already includes a net-to-gross thickness parameter.

The 3D model has been cut to keep only the parts that were deeper than 800 meters in order to insure that the stored CO_2 would be in a dense state, either as liquid or in a supercritical state. Moreover, a maximal depth of 3500 meters was imposed to limit too important future operation costs [9]. The storage calculations were then realized only in the parts between the depths of 800 and 3500 meters (Figure 6). Table 1 presents the calculated volumes of the potential reservoir at the basin scale.

Table 1. Calculated volume of the Cairnside and the Covey Hill formations.

Formation	Number of cells	Calculated volume (km^3)	Calculated volume (m^3)
Cairnside	129,152	1451	1.451×10^{12}
Covey Hill	306,128	3440	3.440×10^{12}

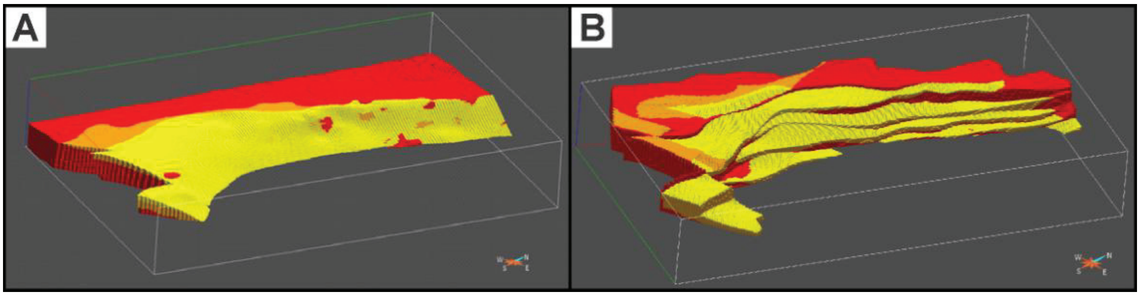

Fig. 6. 3D voxel models of the a) uniform and b) faulted basins. The Cairnside and Covey Hill formations are between than 800 and 3500 meters depth relative to DEM. Yellow: Cairnside Formation. Orange: Covey Hill Formation. Red: Precambrian basement. Vertical exaggeration: 5X.

4.4. Temperature (T)

Temperature in the basin must be known in order to determine the density of CO_2 and is defined by equation 2:

$$T = T_{surface} + (\text{depth} \times \text{geothermal gradient}) \quad (2)$$

Depth is in meters. Temperature (T) is in °C. Geothermal gradient is in °C/m. An average temperature of 8°C is assumed at the surface in the St. Lawrence Lowlands basin. The calculated average temperature gradient of the basin is 19.86°C/km or 0.0199°C/m based on well data:

$$T = 8^{\circ}C + (\text{depth} \times 0.0199\ ^{\circ}C/km) \quad (3)$$

4.5. Pressure (P)

Pressure in the basin must also be known in order to determine the density of CO_2:

$$P = \text{depth} \times \text{pressure gradient} \times 1.1 \tag{4}$$

Depth is in meter. Pressure is in MPa. Pressure gradient is in MPa/m. A pressure of 0 MPa is assumed at the surface. Calculated pressure is increased by 10% to account for pressure increase from injection process. Subsurface pressure is calculated with the pressure gradient of the St. Lawrence Lowlands basin based on the well data. The calculated pressure gradient is 0.0098 MPa/m:

$$P = \text{depth} \times 0.0098\ \text{MPa/m} \times 1.1 \tag{5}$$

4.6. CO_2 density in depth (ρCO_2)

Once the temperature and pressure of the reservoir rocks are known, they are fed into a FORTRAN program which calculated the CO_2 density in every voxels of the model. This application was developed at the Ruhr-Universität Bochum and is based on the work of Span and Wagner [11].

5. Results

The storage capacity is calculated directly in the GOCAD® software following equation 1 which is applied to each cell of the 3D models. The individual cell capacities are summed up in order to get the total capacity for the complete formation. Three capacities are calculated for each formation according to the three difference efficiency factors (*E*) (Table 2).

Table 2. Capacity of CO_2 in gigatonnes in the Cairnside and Covey Hill formations with different efficiency factors for clastics units.

Formation	**Capacity with E(P_{10}) (gigatonne) uniform / faulted basin**	**Capacity with E(P_{50}) (gigatonne) uniform / faulted basin**	**Capacity with E(P_{90}) (gigatonne) uniform / faulted basin**
Cairnside	0.16 / 0.11	0.65 / 0.42	1.74 / 1.14
Covey Hill	0.54 / 0.70	2.11 / 2.76	5.69 / 7.44
Total	**0.70 / 0.81**	**2.76 / 3.18**	**7.43 / 8.58**

6. Conclusions

To illustrate these figures in a more relevant way, it is useful to compare the amount of CO_2 generated by Québec's industrial sector to the province's storage capacity in Table 2. The large emitters (more than 100,000 tonnes of CO_2 per year) generate 20 millions tonnes of CO_2 per year in the Province of Québec [3]. Thus the St. Lawrence Lowlands basin could theoretically store CO_2 emissions of the province during 35 to 429 years which corresponds to the storage capacities calculated for a uniform basin with a P_{10} efficiency factor and for a faulted basin with a P_{90} efficiency factor, respectively (Table 2).

It is also interesting to compare the storage capacity of the two 3D geological models. The Cairnside storage capacity is higher with a 3D uniform basin model whereas it is the contrary for the Covey Hill with a higher storage capacity for the 3D faulted basin model (Table 2). However, the differences are not significant and the more simple 3D geological model of a uniform, or unfaulted basin, is a first acceptable approach for a regional or basin-scale storage capacity assesment.

Acknowledgements

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